

TRAJECTORY METHOD OF MAKING SHORT-RANGE FORECASTS OF DIFFERENTIAL TEMPERATURE ADVECTION, INSTABILITY, AND MOISTURE

JAMES F. APPLEBY

Hydrometeorological Section, U. S. Weather Bureau, Washington, D. C.
[Manuscript received March 22, 1954; revised August 16, 1954]

ABSTRACT

A method is presented of forecasting indices of the strength of horizontal differential temperature advection, instability, and moisture—factors which have been found useful in locating areas of moderate to heavy rainfall. Carefully analyzed data from charts currently used in most forecast programs are used. Examples of the techniques and several cases giving the forecast of parameters and the corresponding observed rainfall are shown. Also included is a comparison of forecast areas of horizontal differential advection and tornado occurrence.

INTRODUCTION

The Hydrometeorological Section of the Weather Bureau has been conducting a study of the feasibility of making short-range forecasts of areas of heavy precipitation (1 inch or more per 6 hours). A trajectory method of forecasting the areas and magnitude of differential temperature advection,¹ instability, and moisture has produced some encouraging results when compared with observed rainfall. The purpose of this paper is to describe the procedure and the reasoning which led to its adoption and to present the results of several studies of heavy rainfall cases prepared under the direction of George A. Lott. A comparison of the parameters determined from forecast trajectories and from trajectories as computed from observed winds is made from results of a case study by Lillian K. Rubin. Finally, the association of severe storms with areas of warm differential temperature advection is illustrated with results from a case study by Morton H. Bailey.

Experience of the Hydrometeorological Section in the study of major rainstorms in the United States has indicated that the analysis of observed data by present day techniques does not always offer a satisfactory solution of the mechanisms involved. In the past we have frequently attributed heavy rainfall to: (1) frontal lifting, (2) increased cyclonic turning of the isobars, and (3) convergence in convectively unstable tropical air. However, very similar conditions, as far as they can be observed or inferred from the data, occur on occasions when little or no rain falls. Present theories of storm mechanisms seem to work well in some cases, but not in others. Therefore, it seems that these mechanisms, although contributing, do not fully explain the rainfall—at least insofar as they are observable.

One major difficulty in deriving a satisfactory explanation of many heavy rainfall situations may be the extreme mobility of the atmosphere. As unstable conditions develop, reactions begin immediately to return the atmosphere to equilibrium. Thus the observed data cannot help being affected by these stabilizing influences. It is an observed fact that temperature and moisture do not move horizontally with the winds. This is because the action of the wind field on the existing temperature field creates unstable situations,² and vertical motions result, causing additional changes in the temperature field. However, advecting the physical properties of the air forward should give some indication of where vertical motion should occur and some indication of its strength if indices are chosen to describe adequately conditions accompanying heavy rainfall.

SELECTION OF INDICES

The main sources of energy available for lifting of the air are those of potential energy of temperature contrast and thermodynamic instability. Indices relating to the air temperature (density) horizontally and vertically along with moisture were considered.

Gilman [1] has hypothesized that horizontal differential temperature advection is a cause of vertical motion. He believes it is brought about by the relative rise of the constant pressure surfaces in a layer where the curvature of the advection profile is like that where warm differential advection is at a maximum. This causes divergence aloft and consequently a pressure fall at the surface and convergence in the lower portion of the layer. Erickson [2]

¹ Differential advection is here defined as the finite difference equivalent of the horizontal Laplacian of temperature advection.

² By an unstable situation is meant one in which air of different densities is brought together in such manner as to cause vertical motion either by overturning, or realization of the potential energy of temperature contrast.

in a study of 11 extremely heavy rainfalls has found this to be verifiable in 9 of the 11 cases at 5,000 ft. and in 7 of the 11 at 10,000 ft. So differential temperature advection was one parameter selected. Instability has long been recognized by meteorologists as a source of energy and this was chosen as the second parameter. The importance of available moisture for precipitation, the third parameter, is obvious.

It is postulated that areas showing marked differential warm air advection depict areas where the part of potential energy of temperature contrast is most likely to be expended in lifting the air and that in areas showing convective instability there is a possibility of energy being added after vertical motion starts. Then if sufficient moisture is present heavy rainfall results.

The first problem then was to develop a method of obtaining future trajectories of the air to test the validity of the selected parameters. Undoubtedly, the nature of the approach limits the length of time it can be projected into the future. However, since the total strong vertical motion compared to horizontal motion in the atmosphere is small, the trajectory approach should be applicable up to 18–24 hours.

CONSTRUCTION OF TRAJECTORIES

Since a forecast tool was the ultimate aim, a reasonable balance between time expended, accuracy, and area applicability had to be reached. For some purposes, the trajectory methods described in the literature (c. f. [3] and [4]) are adequate, but for forecasting purposes these have several shortcomings. One is the time required to construct the trajectories. Another is the requirement of a series of prognostic charts which are not routinely available. The chief objection is the departure of the observed winds from the geostrophic. Some very large departures from the geostrophic are observed in many of the major storms in the United States, and probably are an important factor in the heavy rainfall mechanism.

Trajectories computed from observed wind data are accurate for short intervals, but translation and changes in shape of the pressure systems, with time, limit their applicability. Since Gustafson [5] has shown that there is some reason to believe ageostrophic winds occur in the same location relative to a moving system, allowances for the movement, changes in shape, and intensity of the systems must be made to avoid discarding the ageostrophic flow. With these allowances fairly accurate trajectories can be drawn from the information on the observed chart by the use of acetate overlays, shifted to allow for movement and changes in shape of the systems. Trajectories for the 850-mb. level drawn by this method approximate those computed by the accepted methods and can be drawn over the eastern United States in a relatively short time. No attempt was made to draw trajectories over the Plateau Region for the 850-mb. level for the obvious reason that this level is below the surface there.

The most accurate trajectory would be one made by selecting very short time intervals and drawing vectors from the winds, making allowance for the movement of the pressure systems. The decision to use an average trajectory for periods of up to 9-hour intervals was made after balancing the time required for preparation against the accuracy of the two methods.

To explain the details of the adopted procedure, an example of preparing the trajectories from the observed 0300 GMT 850-mb. chart, October 26, 1953, to 1200 GMT and 1800 GMT the same day, is discussed. Since the advection of temperature and the advection of moisture are the end results, they have been included.

Step 1. Analysis.—The 850-mb. chart (supplied by the WBAN Analysis Center) is prepared by drawing isotherms at intervals of 2° C.—carefully drawing for every temperature unless it is obviously in error. Dew-point isotherms are drawn for intervals of 4° C., except in areas with dewpoints above 8° C. where the analysis is made for every 2° C. On completing this analysis, future positions of the pressure systems (Highs, Lows, ridges, and troughs) at 0730 GMT and 1500 GMT³ are sketched in. These are the locations of the systems at the midpoints of the periods for which trajectories are needed. These future positions are based on extrapolation, the WBAN Analysis Center 30-hour prognostic charts, and the analyst's judgment when the two former disagree radically. If the pressure systems differ significantly in their rates of movement the region influenced by each is outlined. Any intensification or filling of the pressure systems is converted into its effect on the winds and noted on the chart as a percentage increase or decrease of the wind speed. In the work done to date, anticipated changes in wind direction relative to the moving system have not been considered.

Step 2. Trajectories.—A sheet of clear acetate is superimposed on the analyzed chart and check marks placed on convenient latitude and longitude intersections for later reference. The future positions of the pressure systems are traced lightly on the acetate and points are selected for starting points of the trajectories. (See fig. 1.) The spacing and number of points necessary to determine the changing isotherm field varies with the situation, but with experience it can be determined quite closely. Points between the present and the first future position of the pressure feature should not be trajected since shifting of the acetate would put the points to the rear of the feature. In most cases this area is not large and by examination of the wind field, isotherms from this area can be drawn. In rare cases where the area is large, shorter time intervals can be used, for example, two 4½-hour periods instead of one 9-hour period can be selected to draw several trajectories in this area.

³ Since radiosonde and precipitation observations begin shortly after the hour, the time interval between the 0300 and 1230 GMT observations is considered as 9 hours, that between 1230 and 1830 GMT as 6 hours.

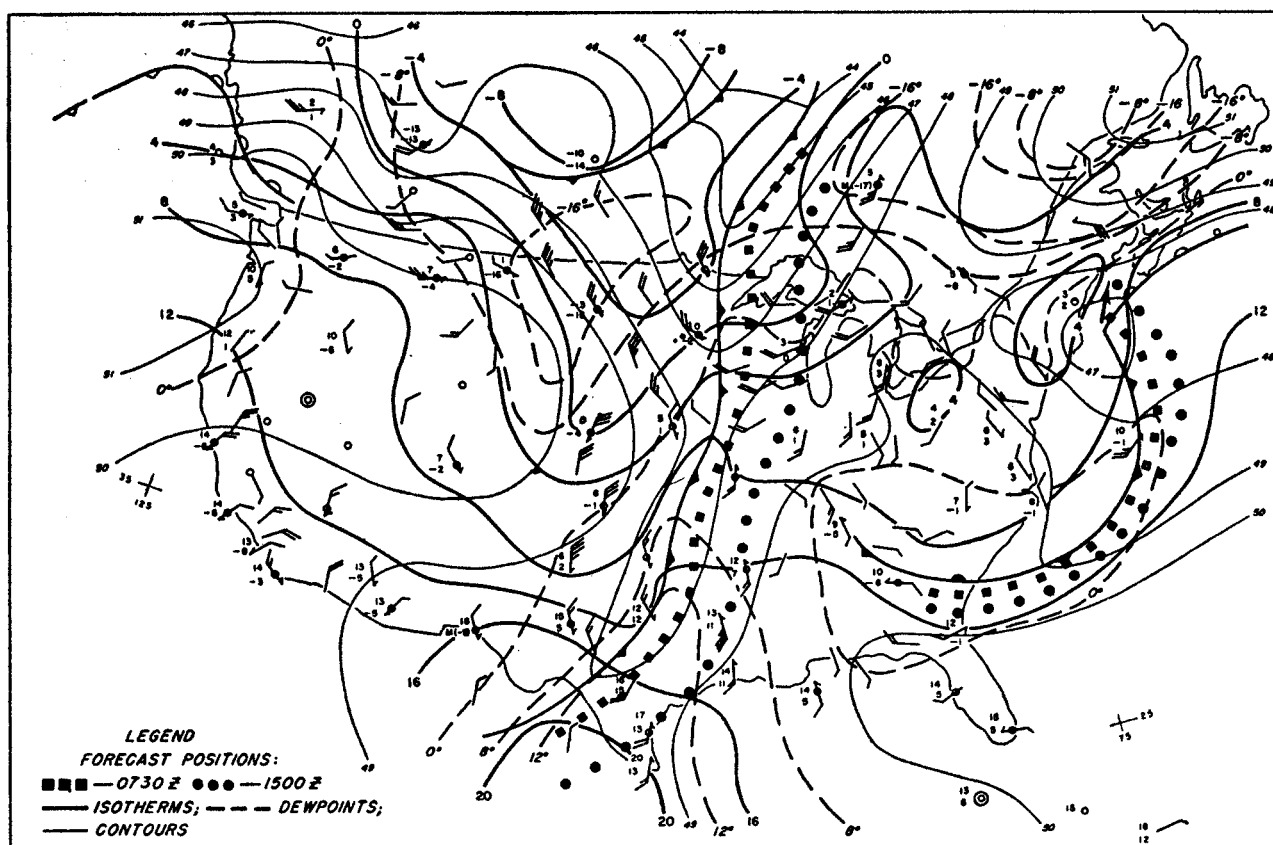


FIGURE 1.—850-mb. chart for 0300 GMT, October 26, 1953 with forecast trough positions at the midpoints in the time periods for which trajectories will be computed as a first step in the forecast of areas of heavy rain. See following figures for successive steps in the procedure.

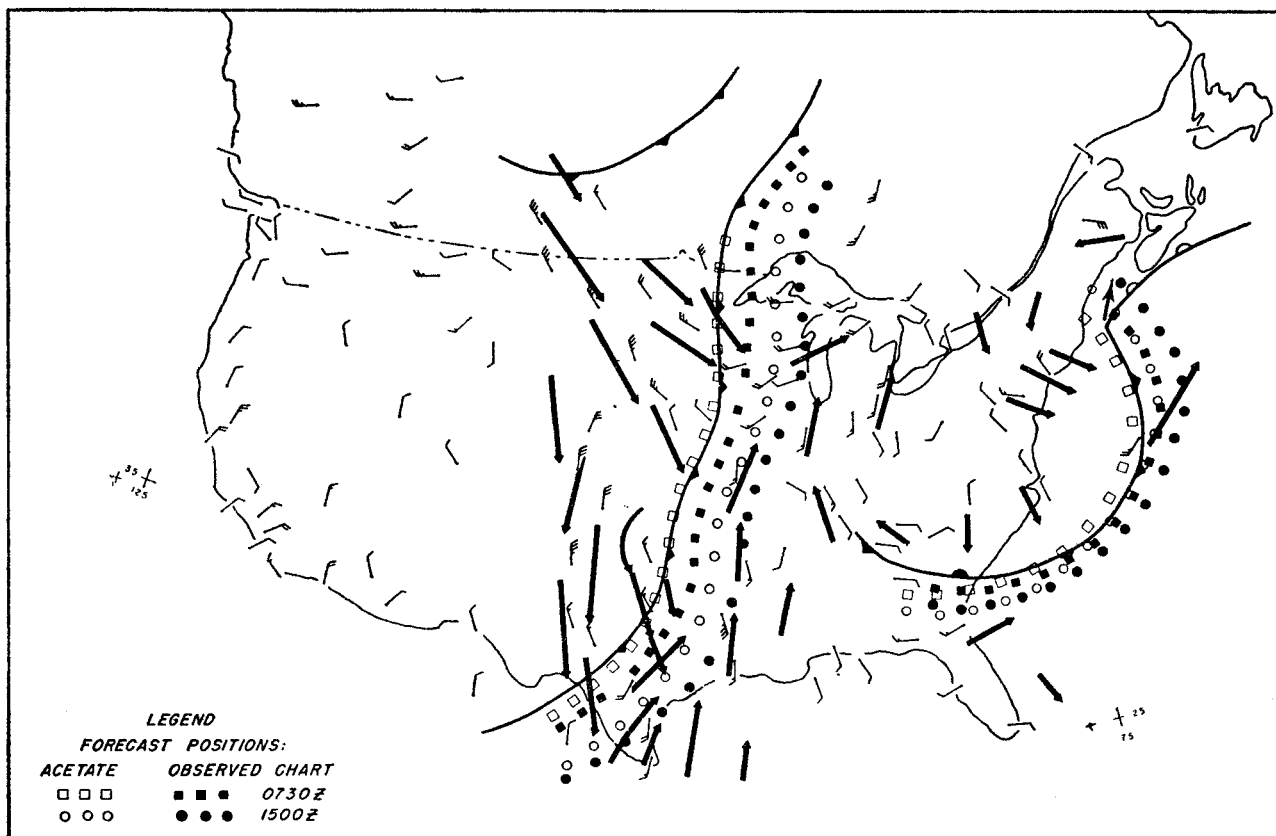


FIGURE 2.—Forecast trajectories for the period 0300-1200 GMT, October 26, 1953 showing position of the acetate overlay on the observed map (0300 GMT, October 26, 1953) when these trajectories were computed.

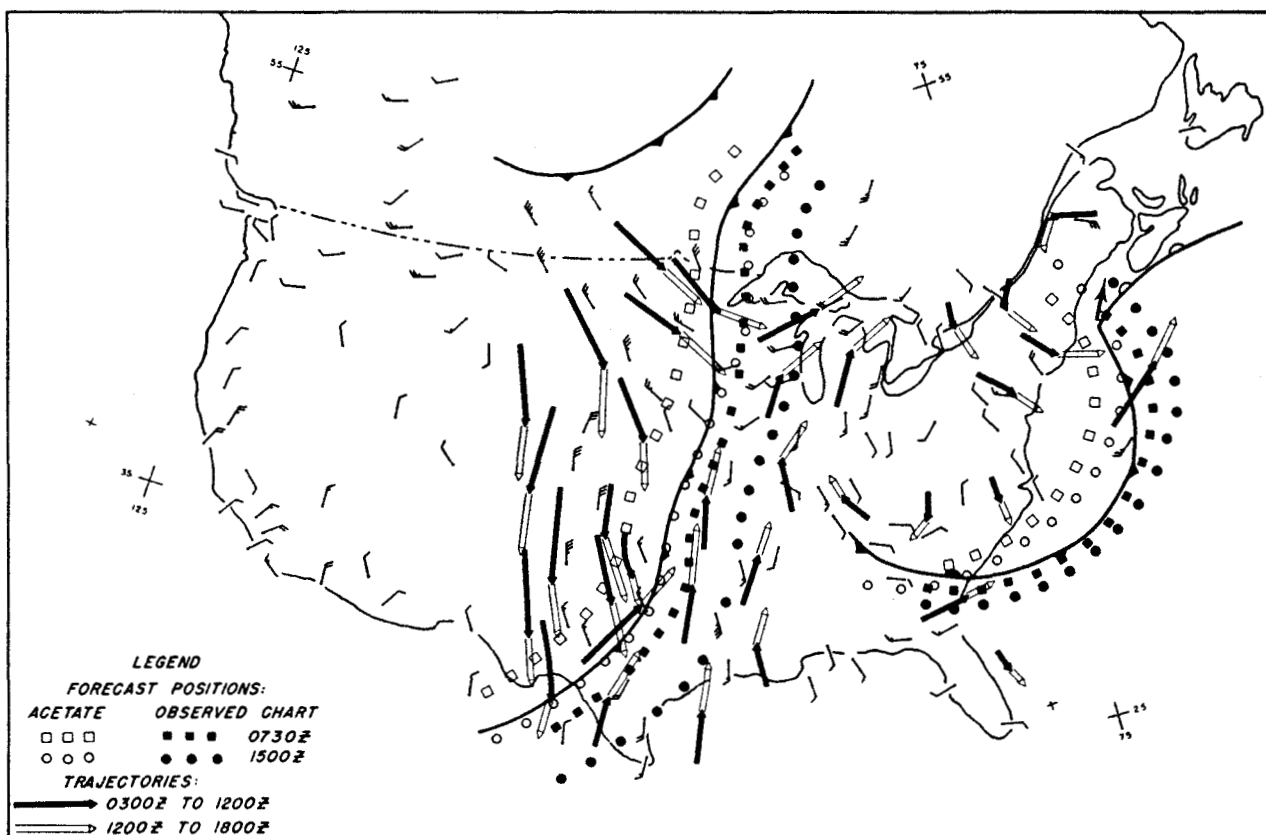


FIGURE 3.—Forecast trajectories for the periods 0300-1200 GMT (solid arrows) and 1200-1800 GMT (open arrows) October 26, 1953 showing position of acetate overlay on observed map (0300 GMT, October 26, 1953) when 1200-1800 GMT trajectories were computed.

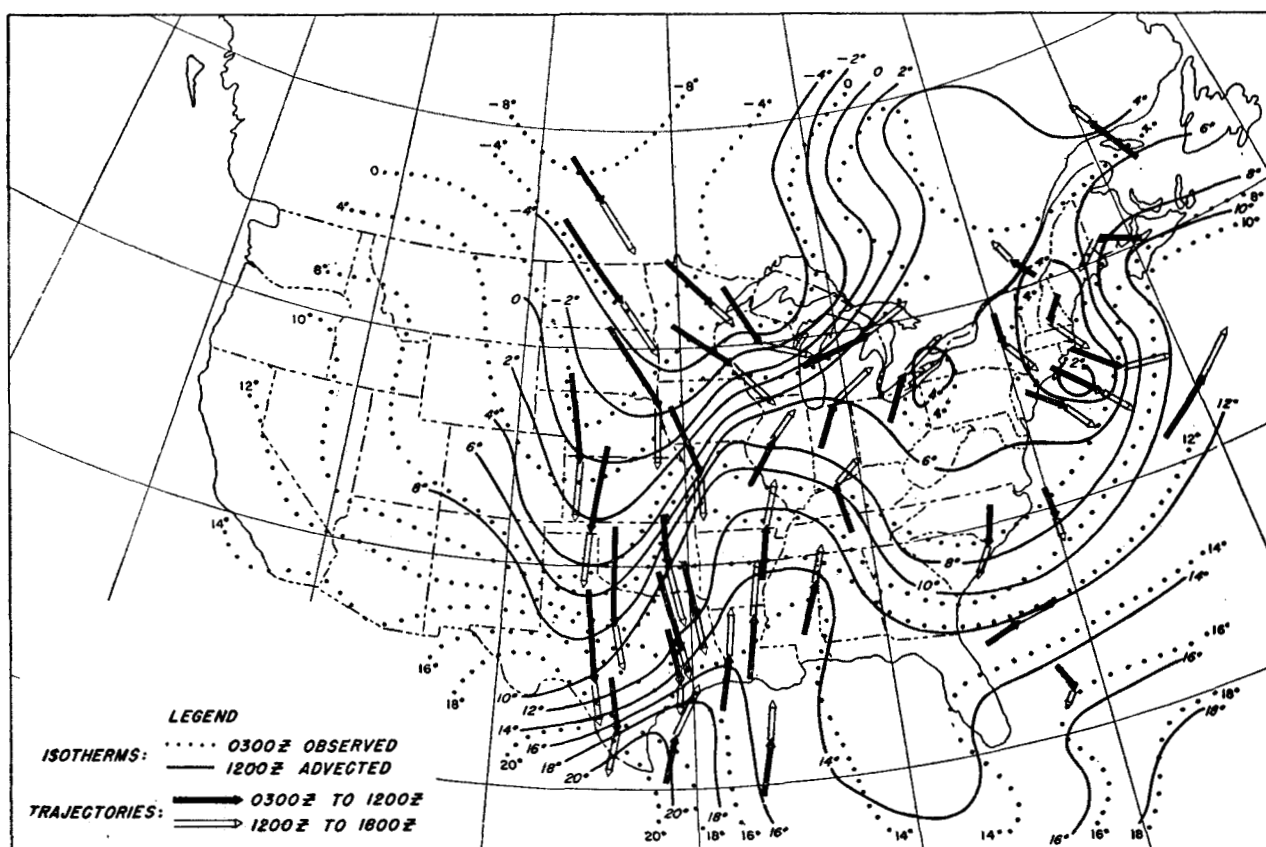


FIGURE 4. Forecast 850-mb. temperature field for 1200 GMT, October 26, 1953 (solid lines) obtained by advecting the 850-mb. temperature observed at 0300 GMT (dotted lines) from the beginning point to the tip of each solid arrow. The forecast of the 1800 GMT temperature field (needed in the next step but not shown here) is obtained by advecting the 0300 GMT temperature to the tip of the open arrow.

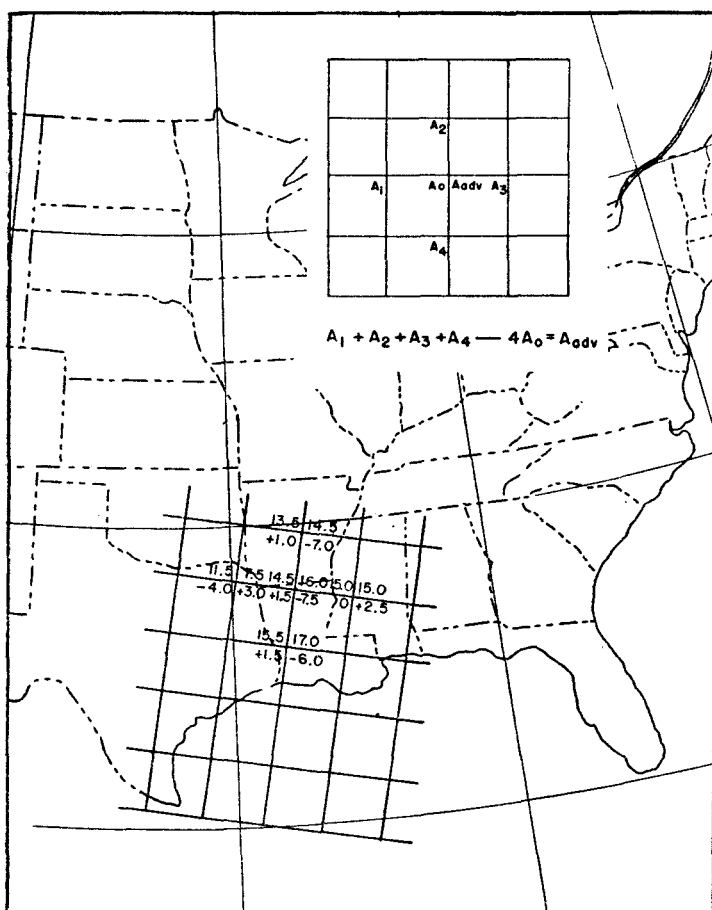


FIGURE 5.—Sample of computation of forecast differential temperature advection for the period 1200–1800 GMT, October 26, 1953 using the forecast 1200 and 1800 GMT, temperature fields. See text p. 325 for derivation of numerals in grid over Louisiana.

After selecting the points, each movement area is considered independently. (Note that in fig. 1 movement of the system in the central United States is quite different from that of the Low over New England.) The acetate is then moved so that the 0730 GMT position of the pressure system sketched on it coincides with the original position on the observed chart. After the acetate is shifted, trajectories are drawn from each previously located point using the observed winds directly beneath the point and along its path and determining the vector length from an average of the wind speeds along the path. A scale converting wind speed to distance allows a good many trajectories to be drawn in a short time (fig. 2). Where the change in shape of the system is great, the fitting should be done in two steps. (See fig. 3.) Note that in the north the trough line on the acetate is well to the east of the trough on the observed chart when the fit is good in the south. Before trajectories are drawn in the northern section, the acetate should be shifted over the trough line on the observed chart. Each movement area is treated independently and when a trajectory moves from one movement area to the next, it is considered with the new area when the trajectory for the next period is drawn.

When the first period trajectories are completed, the acetate is shifted so that the second forecast position of the pressure system overlies the original position on the observed chart. Trajectories are then extended from each arrow tip using the same procedure (fig. 3).

Trajectories are now completed for this level. Trajectories for other levels can be made in the same manner to allow an examination of vertical structure.

Although the method is somewhat rough, it is the only one offered at this time which allows a forecast of the future trajectories over the eastern United States capable of completion in less than one hour. The accuracy of the trajectories depends on a subjectively forecast movement of the pressure systems. However, practically all forecasts made today are based on a prognosis of the movement of pressure systems, and the first part of the trajectories are based on observed data. Therefore, the subjectivity should not prove too great an objection. Small errors in forecast movement do not appreciably alter the trajectories, as the winds in most pressure systems change gradually from one area to another outside the frontal zone.

Step 3. Advection of temperature and moisture.—Advection of temperature and moisture by the trajectories is accomplished by returning the acetate, by the reference marks, to its original position. Another acetate, with reference marks, is superimposed and the tips of the first trajectories labeled with the temperatures at the beginning points. The forecast isotherms for 1200 GMT are then drawn using these points, the wind flow as depicted by the trajectories, and the previous isotherm pattern as guides (fig. 4). This is repeated for the total trajectories to obtain the 1800 GMT advected temperature pattern. Dewpoint patterns are advected in the same way. Analysis of the changes in structure horizontally and vertically can now be made.

DETERMINATION OF PARAMETERS FROM THE ADVECTED DATA

The determination of the parameters, although they are given in Celsius degrees is not to be construed as a forecast of actual observable values; the parameters serve merely as indices of the relative strengths of the measured items.

DIFFERENTIAL TEMPERATURE ADVECTION

Differential temperature advection as a cause of vertical motion applies to a layer, and according to Gilman [1], its greatest effect results from differential advection in the lower layers. The 850-mb. level rather than the surface has been chosen as representative of the lower layers. Several observations of wind structure in storms seem to indicate that the 900- to 925-mb. levels would be even more representative of the region where this phenomenon is strongest [6]. Unfortunately, however, the necessary data are not available for those levels.

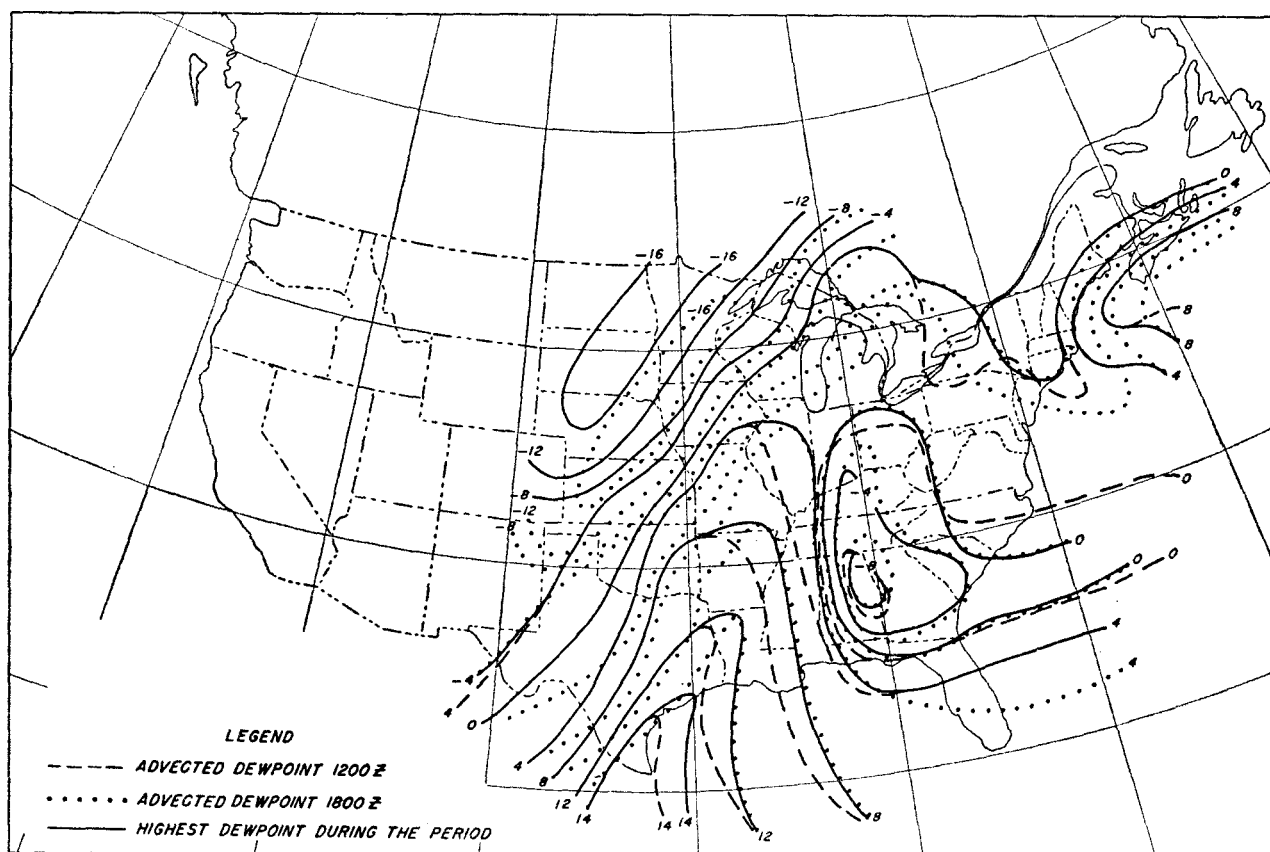


FIGURE 6.—Forecast moisture fields for 1200 and 1800 GMT, October 26, 1953 obtained by advecting the observed dewpoints along the trajectories in the same way the temperature was advected. Also shown is the field of the highest dewpoint forecast for the interval 1200–1800 GMT.

To determine the differential temperature advection for a specified period, the advected temperatures are needed at the beginning and end of the period. For the particular purposes of the study, 6-hour periods seem adequate. For short duration phenomena, perhaps 3-hour periods should be used. The procedure adopted to obtain the quantitative values of differential advection from the temperature patterns obtained above was developed by Richard C. Bourret formerly of Hydrometeorological Section and is as follows: An acetate marked with a grid of 2-degree latitude squares is superimposed on the temperature charts. The temperature at the beginning of the period is marked in the upper left of each grid intersection and that at the end of the period in the upper right (fig. 5). Differences A are then entered in the lower left.

Since differential advection involves the relationship of a point to its surroundings the Laplacian of the advection A_{ADV} is found for each grid intersection from the following formula $A_1 + A_2 + A_3 + A_4 - 4A_0 = A_{ADV}$, where A_1 , A_2 , A_3 , A_4 are the temperature changes at the points west, north, east, and south respectively of point with change A_0 . This temperature change at the central point as compared with the change around it is plotted in the lower right of the grid intersection. Negative values indicate differential warm-air advection; positive values indicate differ-

ential cold-air advection. The pattern of differential advection is then analyzed. See figure 7A.

MOISTURE

The moisture pattern is analyzed from the advected dewpoints. The values for the period are determined from those obtained at the beginning and end of the period. It is assumed that the movement between these two is a smooth progression. Connecting the areas between equal dewpoint isolines at the beginning and end of the period provides a picture of the maximum moisture existing over the area during the period (fig. 6).

INSTABILITY

To obtain an index of the vertical stability, the Showalter [7] technique⁴ is applied to the advected temperatures and dewpoints using 700 mb. instead of 500 mb. as the reference level. This choice was made, in part, because a comparison of conditional instability in large storms showed that the departure from average conditions is greater in 850-mb. parcels lifted to the 700-mb. level than in 850-mb. parcels lifted to the 500-mb. level. The

⁴ The parcel is lifted along the dry adiabat until saturated, then along the moist adiabat to the reference level where the temperature is compared to the observed temperature. When the lifted temperature is colder than the observed at the reference level, the departure is noted as positive, and vice versa.

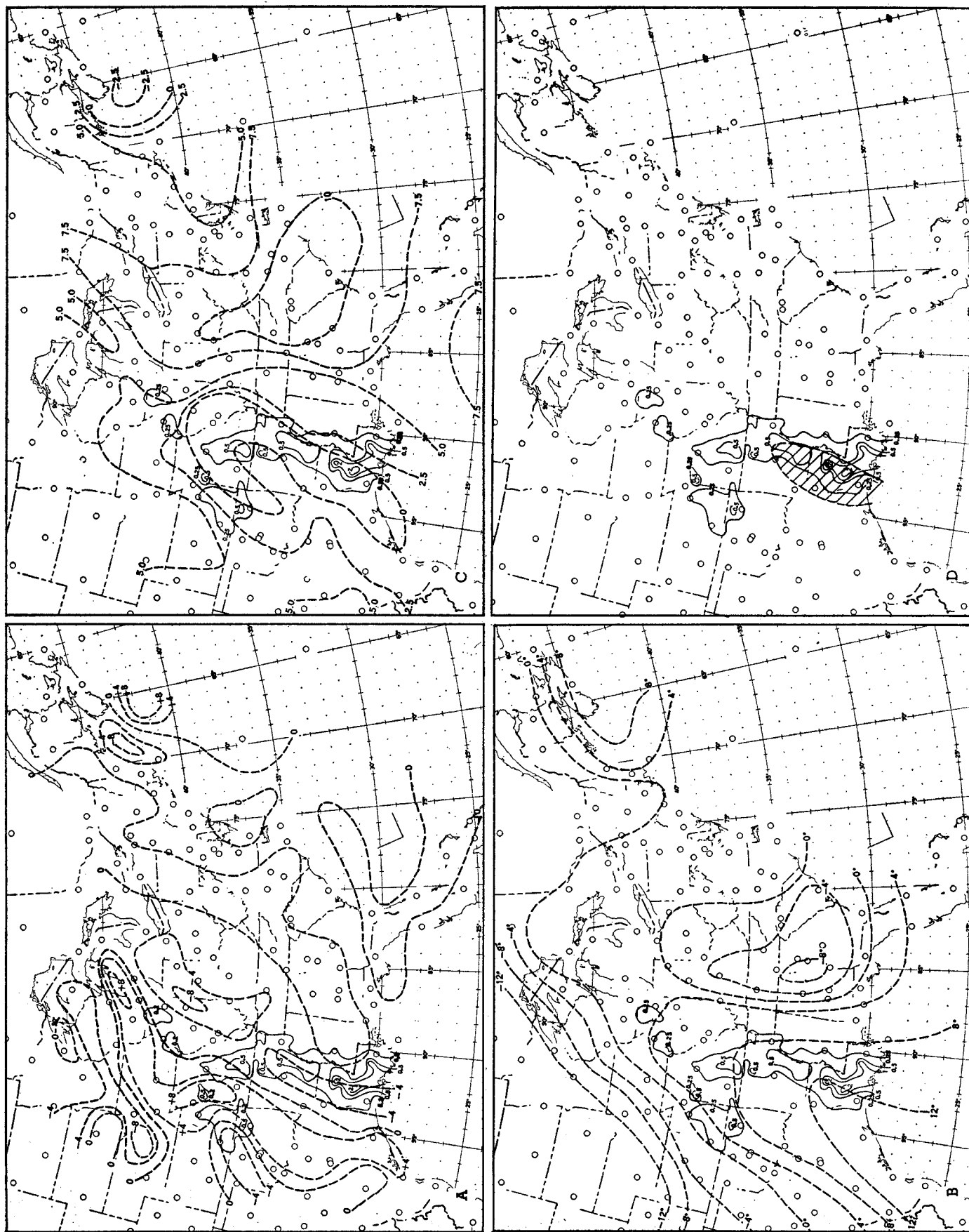


FIGURE 7.—Forecast parameters and forecast heavy rain area each superimposed on isohyets of observed precipitation (thin solid lines) for period 1200-1800 GMT, October 26, 1963. (A) Forecast differential temperature advection field resulting from operations shown in figures 1-5. (B) Forecast dewpoint for the period. (C) Forecast stability computed by the Showalter technique using the advection technique and the 700-mb. rather than the 500-mb. level as the reference level. (D) Forecast heavy precipitation area (hatched) based on coincidence of centers of intensity of the parameters shown in parts A, B, C. Note correspondence with area of observed rain.

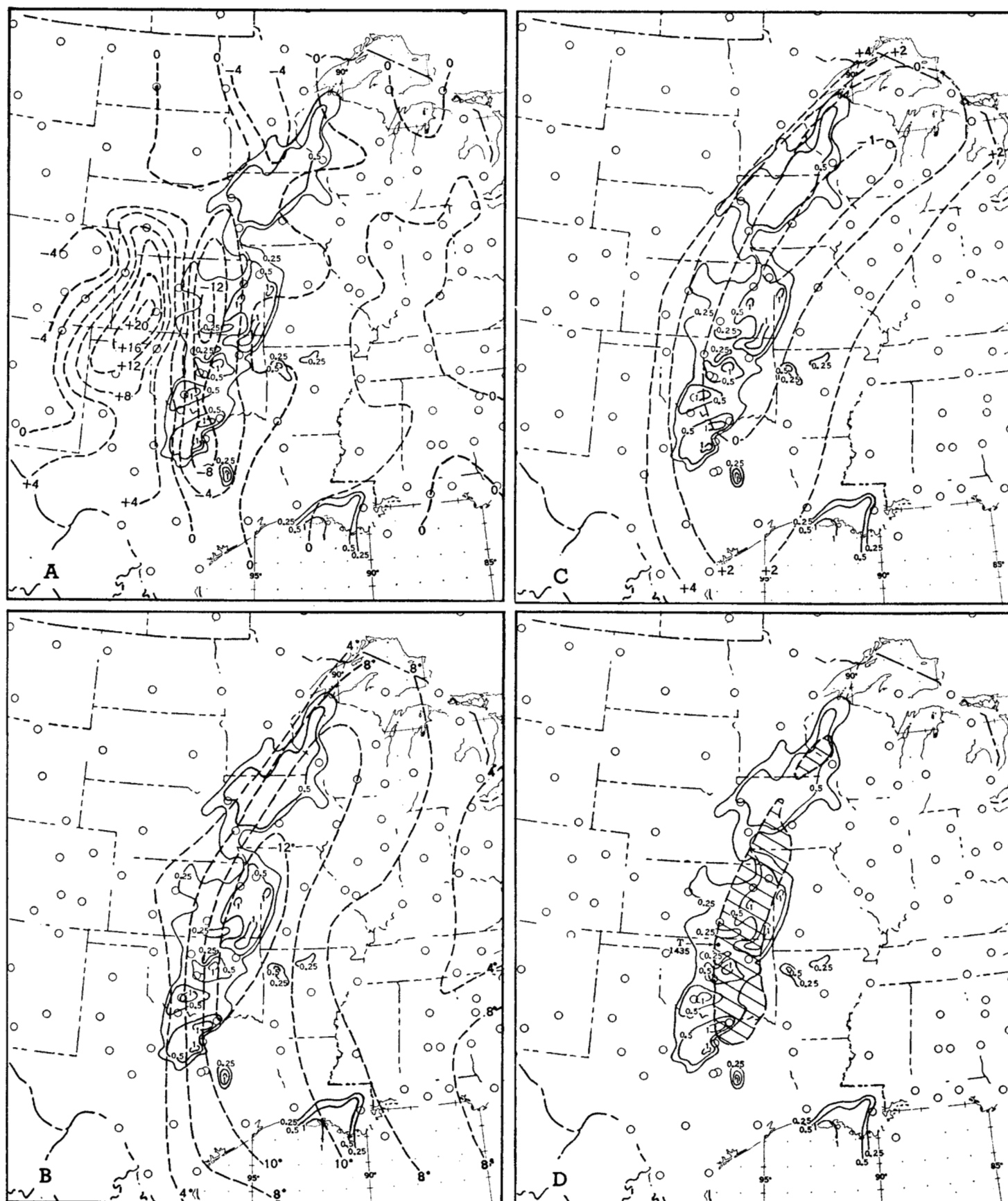


FIGURE 8.—Forecast parameters (A—differential temperature advection, B—dewpoint, C—stability) and (D) forecast heavy rainfall area each superimposed on isohyets of observed precipitation (thin solid lines), 1200–1800 GMT, November 19, 1953.

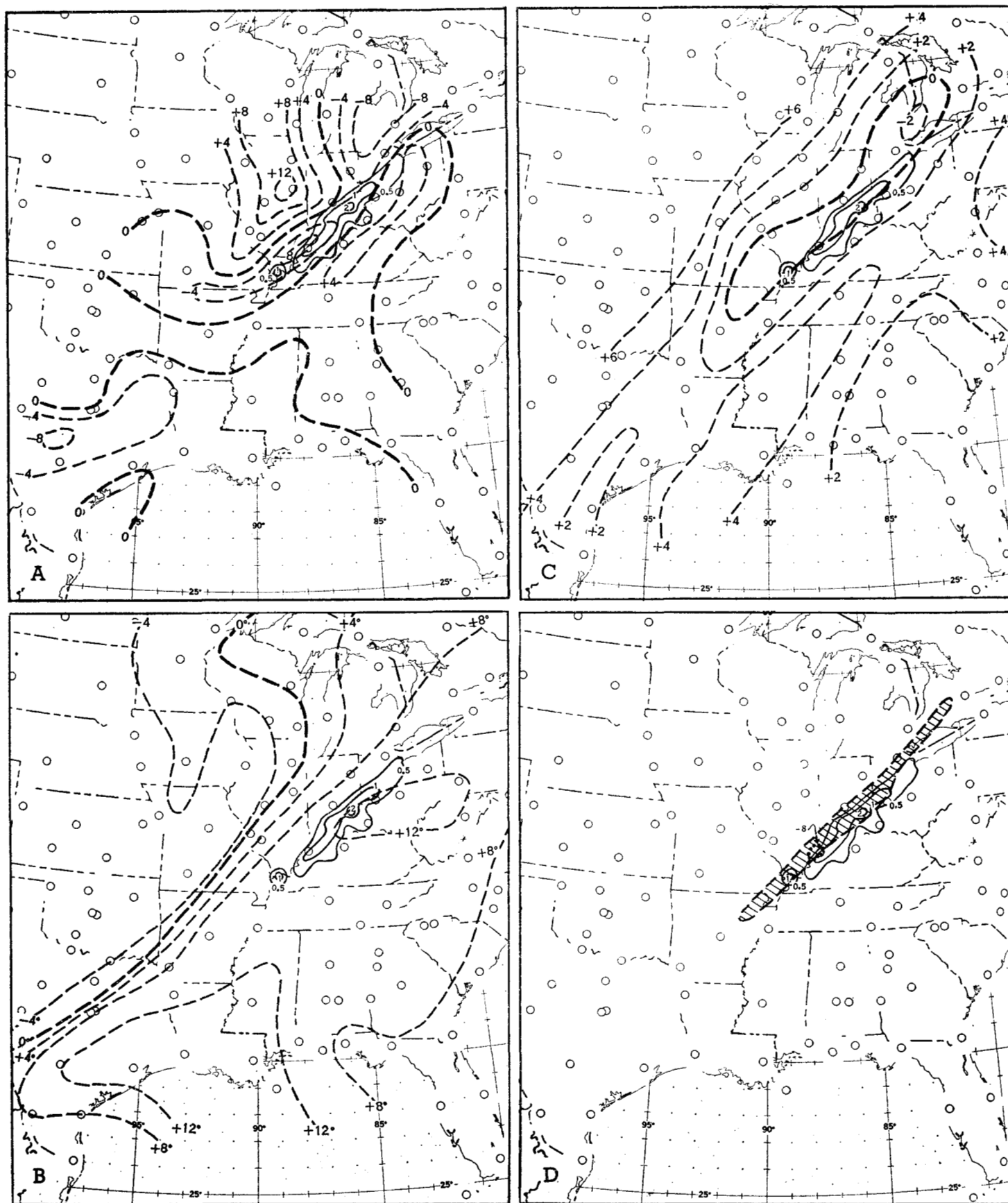


FIGURE 9.—Forecast parameters (A—differential temperature advection, B—dewpoint, C—stability) and (D) forecast heavy rainfall area each superimposed on isohyets of observed precipitation (thin solid lines), 0300-0900 GMT, December 7, 1953. In (D) center of warm differential advection is again shown (dotted).

difficulty in handling the high winds at the 500-mb. level on the small-scale chart on which it is now plotted also influenced the choice.

The conditional instability is computed for both periods and combined by the same method used for the dewpoints. See figure 7C.

TESTS OF METHOD AND PARAMETERS

Comparison of the patterns and intensities of these parameters with rainfall areas observed during the periods permits a test of both the trajectory method and the chosen parameters. Both have to be reasonably correct to obtain any correspondence between the areas indicated by parameters and the areas of observed rain. Slight displacements in areas of heavy rainfall and the areas indicated by the parameters suggest the parameters are probably correct but the trajectories are inaccurate. If no correspondence in areas is obtained it indicates either the reasoning behind the trajectory method, the method itself, the parameters chosen, or all three are incorrect.

FORECAST PARAMETERS vs. RAINFALL

To test the trajectory method and the parameters, daily forecasts of the parameters for the period from 1200 GMT to 1800 GMT have been made from 0300 GMT data for October and November 1953. The example used to explain the procedure for determining trajectories (fig. 7) is one of these. George A. Lott and Lillian K. Rubin have made special forecasts of the parameters in several heavy rainfall cases without previous knowledge of the exact location of the heavy rain. A few of these will be shown along with the corresponding rainfall.

In figure 7 the forecast values of the parameters from the previously discussed example are superimposed on the isohyets of observed rainfall during the period. Note in figure 7A that the areas with rainfall are usually where warm differential advection has been forecast. The exception in northern Illinois is displaced, probably due to the formation of a Low in southeastern Kansas which was not forecast. The Low would cause warm air to flow more toward the northwest than forecast, shifting the differential advection in that direction. To explain the lack of rainfall in areas of strong warm differential advection and the variation in rainfall amounts, one must take the forecast moisture (fig. 7B), and stability (fig. 7C), patterns into consideration. The small rainfall center in southeastern Kansas and northeastern Oklahoma is associated with an area of instability, high differential warm-air advection, and a dewpoint of 4° C. The light rainfall between this center and the north-south band occurred in an area of greater moisture, the same instability, but a high value of differential cold-air advection. The heavy rainfall in Louisiana corresponds closely to high values of all three parameters.

Again in figure 8 the parameters fit the rainfall pattern fairly well; however, in the south where we are dependent

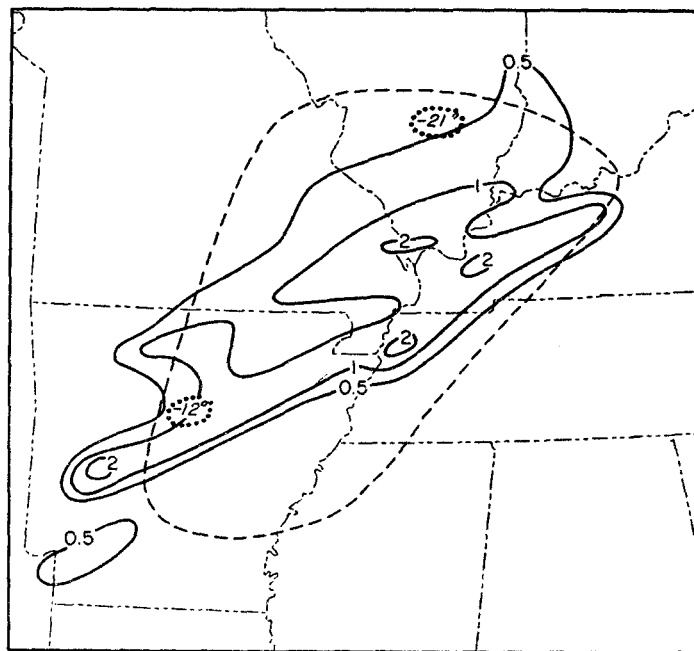


FIGURE 10.—Forecast heavy rainfall area (based on same parameters as shown in figs. 7, 8, and 9) superimposed on isohyets of observed precipitation (thin solid lines) 1500 GMT, March 21 to 0300 GMT, March 22, 1952. The magnitude and position of the centers of areas of warm differential temperature advection are shown by dotted lines.

on data over the Gulf, the high moisture and low stability values cut off before heavy rainfall. There could be several reasons for this. One may be lack of data over the Gulf, another, the effect of the change from over-water to over-land flow.

Experience indicates that the areas of heavy rainfall (approximately 1 inch per 6 hrs.) usually coincide with the areas where differential temperature advection of -2° C. or greater (negatively), dewpoints of 10° C. or higher, and stability of less than 0° C. are forecast to coincide during the 6-hour period. Figures 7D and 8D show these forecast areas as compared to the rainfall for the two previous examples. Figure 9 shows the results of one of the heavy rainfall situations analyzed by Rubin and Lott. Figure 10 shows a comparison of a 12-hour forecast of heavy rain areas with the observed rainfall. The 12-hour forecast is made by combining the forecast areas from two consecutive 6-hour forecasts.

The correspondence of the areas is fairly good considering the inaccuracies in the trajectories and the limitations in determining the original temperature and moisture fields. Forecasts shown in figures 7D and 8D were made using 850- and 700-mb. charts plotted on a scale of 1:12,500,000. A large-scale map increases the precision with which the trajectories can be drawn which in turn might improve the correspondence between the forecast and observed rainfall. Figure 9 was made using charts with a ratio of 1:5,000,000. This perhaps accounts for the better correspondence. (All maps are reproduced here on the same scale.)

A more definite quantitative forecast cannot be made until the effects of the gradient of the differential temperature advection parameter, and the relative importance of

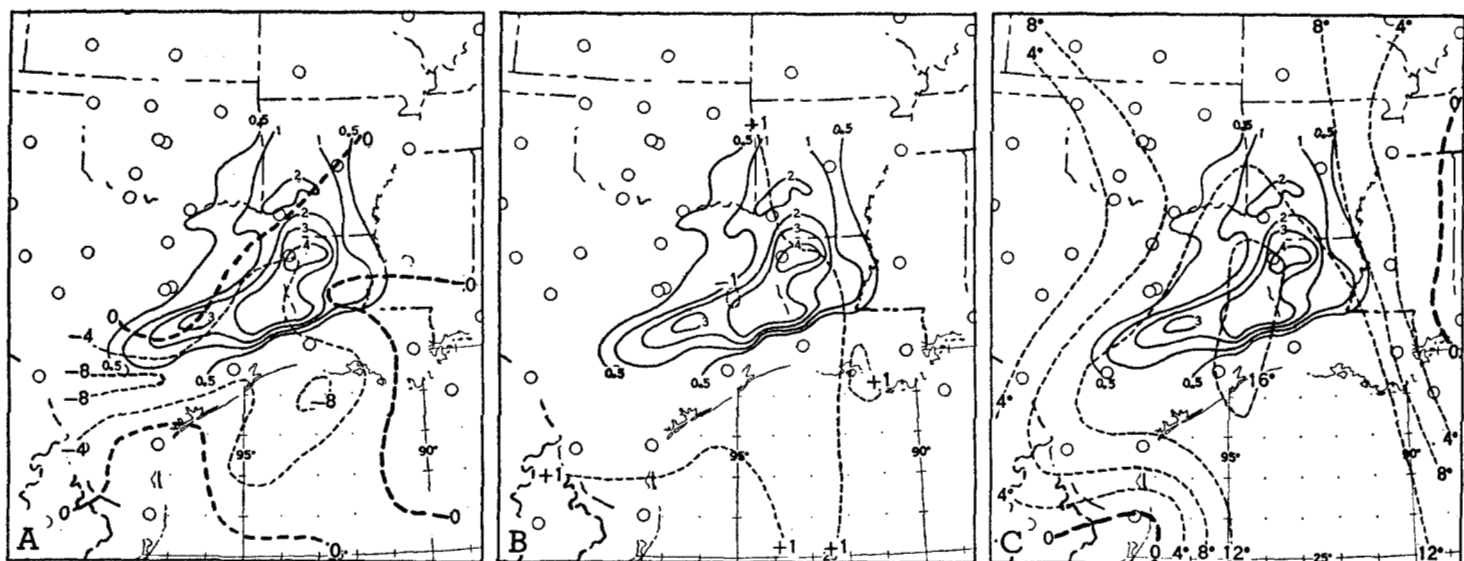


FIGURE 11.—Forecast parameters (A—differential temperature advection, B—dewpoint, C—stability) superimposed on isohyets of observed rainfall (thin solid lines), 0300-0900 GMT, April 29, 1953. These parameters based on forecast trajectories.

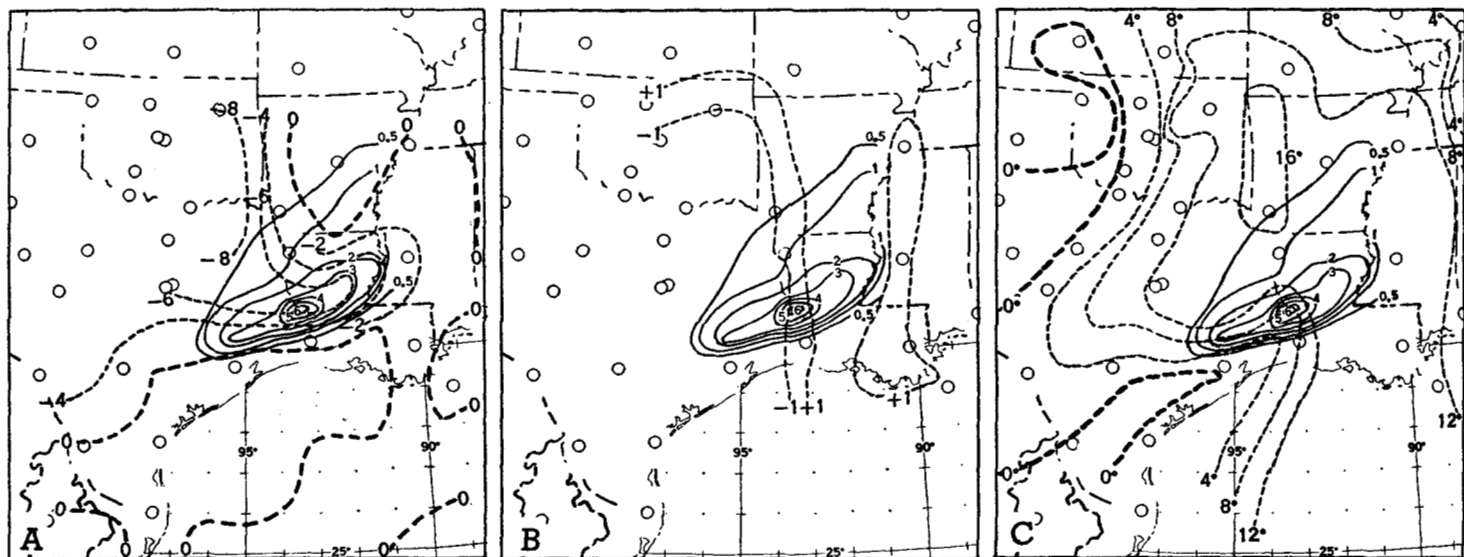


FIGURE 12.—Forecast parameters (A—differential temperature advection, B—dewpoint, C—stability) superimposed on isohyets of observed rainfall (thin solid lines), 0900-1500 GMT, April 29, 1953. These parameters based on forecast trajectories.

the other two parameters, are determined. However, it seems the forecasting of the approximate areas of heavy precipitation would be useful to some interests.

COMPARISON OF THE PARAMETERS DETERMINED FROM FORECAST TRAJECTORIES AND FROM OBSERVED TRAJECTORIES

A comparison of the parameters forecast from the trajectory method and those computed from observed streamlines and their relation to the rainfall pattern has been made by Rubin [8]. The results that follow in this subsection were extracted from her paper.

Exceedingly heavy rain fell over the northern two-thirds of Louisiana, eastern Texas, and southwestern Mississippi on April 28-29, 1953. Many of the values reported were new 24-hr. records, 12.77 inches at Pollock in central Louisiana on the 29th, 12.54 inches at Camp Polk on the

same date. In Mississippi, Vicksburg reported the heaviest 12-hour rainfall of record, 8.73 inches, between 3:10 a. m. and 3:00 p. m. on the 29th. High winds accompanied the heavy rainfall, and a tornado was reported in northern Louisiana just after midnight of the 28th. This situation was used to test the trajectory method for the short-period forecast of heavy rains.

The axis of the differential temperature advection pattern (fig. 11) at 850-mb. for the first 6-hour forecast period of the April 28-29 storm was coincident with the axis of the northeastern part of the precipitation area for the same time. Westward, however, the axis of the differential advection pattern became increasingly east-west. Nevertheless, almost the entire precipitation area lay within the area of warm differential temperature advection. A flaw in the pattern was the center of warm

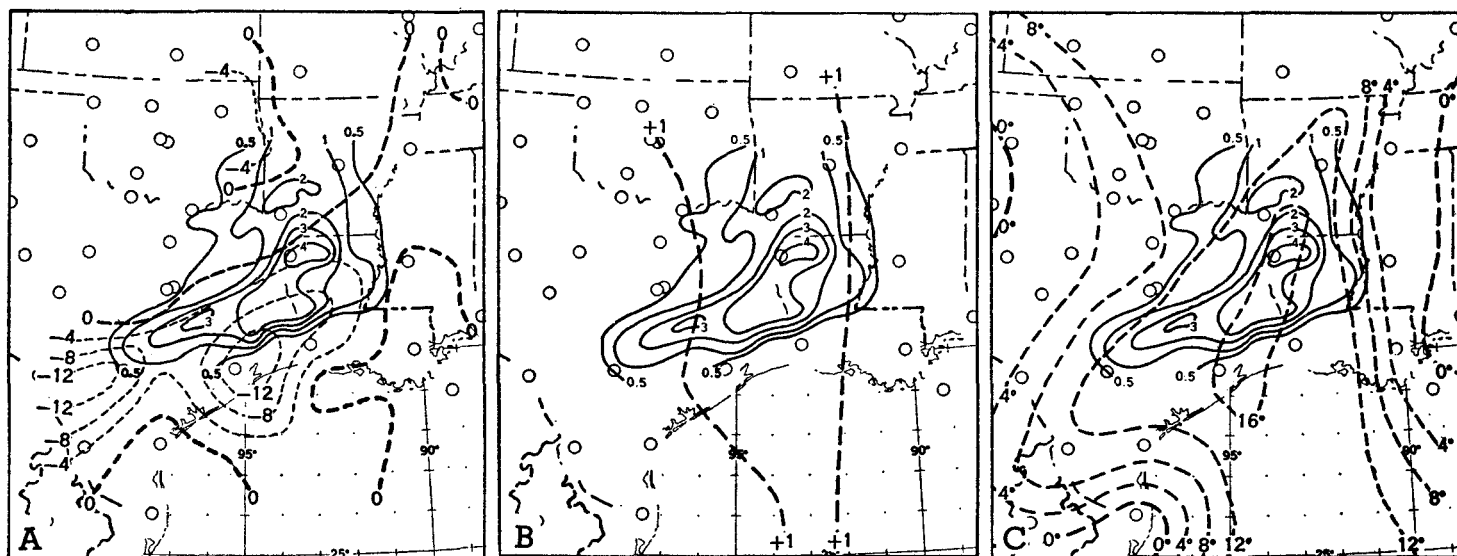


FIGURE 13.—Forecast parameters (A—differential temperature advection, B—dewpoint, C—stability) superimposed on isohyets of observed rainfall (thin solid lines), 0300-0900 GMT, April 29, 1953. These parameters based on observed trajectories for the period. Compare with figure 11.

differential advection in the Gulf, south of the edge of the rain area. Although the greatest part of the precipitation area lay within the $+1$ limit of the stability parameter, a part of the area was cut off. The moisture pattern (dewpoint parameter) forecast for the first period agreed well with the precipitation pattern.

For the second 6-hour forecast period, the axis of the differential temperature advection (fig. 12) was coincident with that of the eastern half of the precipitation pattern. Although the axis of the western part of the differential advection pattern turned slightly north of west while the axis of the precipitation was slightly south of west, the entire precipitation area for this period was within the area of warm differential temperature advection. The agreement was closer than in the first period. The area of strong warm differential advection northwest of the rain area caused no concern, for it has been observed in previous cases that when one center of warm differential advection lies upstream from another, the rain will occur with the upstream center. The vitiation of the downstream center is probably due to a distortion of the upstream temperatures as a result of the rainfall there. The $+1$ limit of stability bisected the precipitation area for this forecast period. Although the moisture pattern for the second period indicated a drying-out over part of the precipitation area, there was probably an upwelling from below the 850-mb. level.

The differential temperature advection was also computed for the 700-mb. level for both 6-hour periods. In the first period there was some warm differential advection over the northeastern third of the heavy rain area, while there was cold differential advection over the rest of the precipitation area. In the second period there was cold differential advection over the entire precipitation area.

If the basis for the trajectory method is sound, use of the actual wind flow for the forecast period should improve

the verification. As a test, observed trajectories were constructed for the period from 0300 to 0900 GMT based on streamlines at 0300 GMT and at 0900 GMT, and for the period from 0900 to 1500 GMT, based on streamlines for these two times. The observed trajectories for the first 6-hour period at the 850-mb. level were then used to advect the temperature and dewpoint fields as they existed at that level at 0300 GMT, and those for 700 mb. were used to advect the temperature field at that level. The usual procedure was then applied to the advected data to determine the 850-mb. differential temperature advection, dewpoint, and stability parameters (fig. 13).

The most significant improvement in the resulting pattern of differential temperature advection was that the center of warm differential advection that appeared over the Gulf in the original forecast chart was now situated on land, partially overlapping the heavy rain area. Orientation of the moisture parameter pattern with relation to the precipitation pattern was also somewhat improved. The errors in the original forecast chart appeared to be due primarily to an increase in the speed of the winds that was not forecast. Figure 14 shows a comparison of forecast and observed trajectories. The network actually used in projecting temperatures and dewpoints was far more dense. The lack of a more perfect pattern on the forecast chart based on observed trajectories may be due in part to the sparse wind data available. Stronger winds than those reported may have occurred between stations.

The observed trajectories for the second period were applied to the 850-mb. temperature field as it was forecast for 0900 GMT, and the differential temperature advection for the second period was computed. Surprisingly, the resulting pattern of warm differential advection, figure 15, was very much worse than that originally forecast. There was no apparent reason for this.

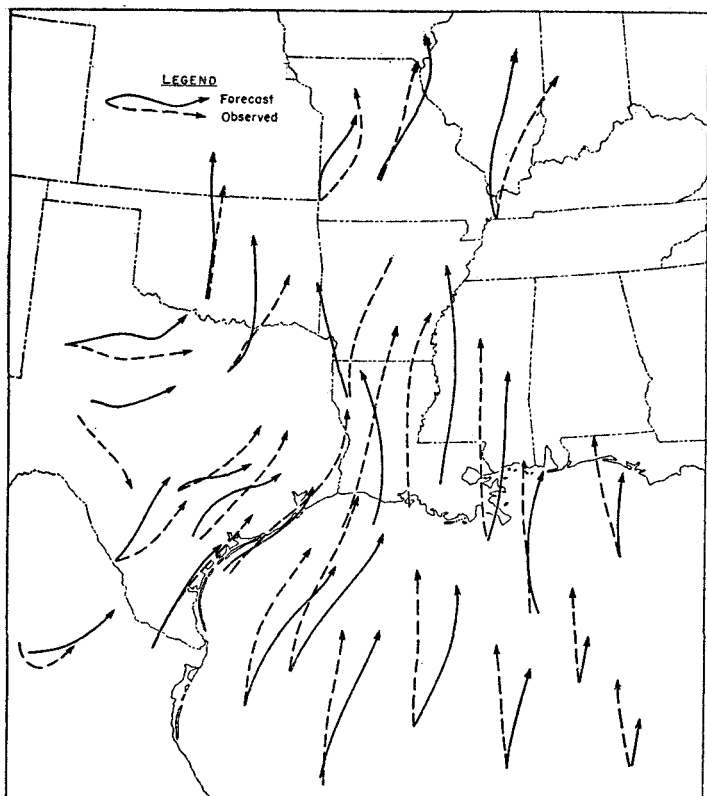


FIGURE 14.—Comparison of forecast and observed trajectories, 0300-0900 GMT, April 29, 1953.

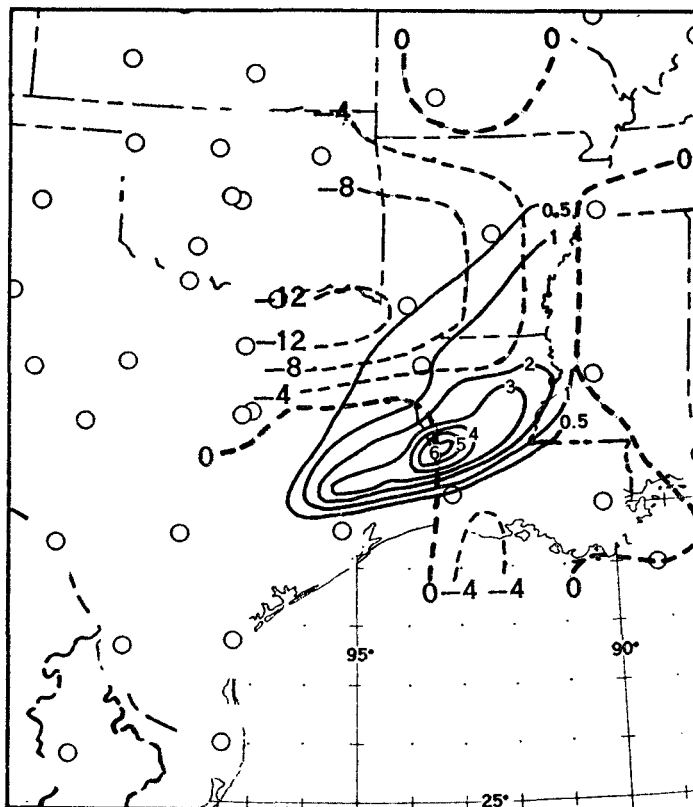


FIGURE 15. Forecast differential temperature advection superimposed on isobars of observed rain (thin solid lines), 0900-1500 GMT, April 29, 1953. This forecast, based on observed trajectories. Compare with figure 12.

FORECAST OF DIFFERENTIAL TEMPERATURE ADVECTION AND TORNADO OCCURRENCE

During the course of the study it was noted that reported tornado occurrences were associated with forecast areas of warm differential temperature advection. As a step toward determining the value of forecasts of differential advection as an aid in tornado forecasting, the tornado situation of June 7-9, 1953, was selected for study by Bailey [9]. The results presented in this section were extracted from his report.

The differential advection for the approximate time of occurrence of the tornadoes of June 7, 8, and 9, 1953, was computed by the method already outlined. Difficulty was experienced in constructing an accurate 850-mb. chart far enough westward into the mountainous terrain to forecast the differential temperature advection for eastern Nebraska on June 7. It was decided to use the 700-mb. chart for 1500 GMT, June 7, and to carry out the process exactly as is ordinarily done on the 850-mb. chart. The resulting forecast for the 6-hour period centered at 2200 GMT, June 7 (fig. 16), shows good agreement with the tornado locations.

The use of the 700-mb. chart in this example raises the question of the generality of results for the Rocky mountain areas and other localities. Some other cases have since been studied by the Hydrometeorological Section using the 700-mb. chart when the area of interest was

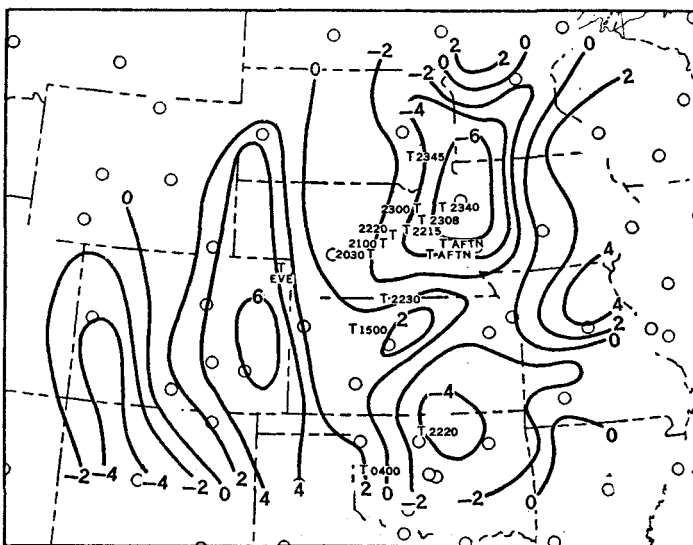


FIGURE 16.—Tornado occurrences plotted on field of forecast differential temperature advection at 700 mb., 1900 GMT, June 7, to 0100 GMT, June 8, 1953. Forecast made from chart for 1500 GMT, June 7.

west of about 95° W. longitude. Results from these cases show better correspondence with areas of rainfall than use of the 850-mb. charts for the same dates. This indicates that the 700-mb. chart should be used in areas where the 850-mb. chart is near or below the surface. However, since low level differential advection is desired, the 850-mb. chart is still recommended for areas where it is near the gradient wind level or above.

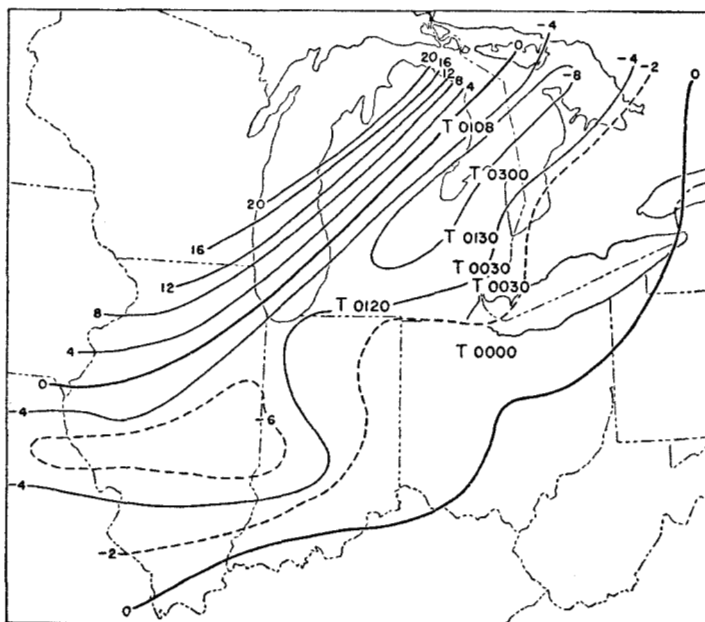


FIGURE 17.—Tornado occurrences plotted on field of forecast differential temperature advection at 850 mb., 0000-0600 GMT, June 9, 1953. Forecast made from chart for 1500 GMT, June 8.

The differential temperature advection was computed from the 850-mb. chart 12 hours in advance for the approximate time of occurrence of the highly destructive tornadoes at Flint, Mich., and nearby areas on June 8, 1953, and is shown in figure 17. The tornadoes occurred within the area of largest values of warm differential advection. Even though very small values, which might be considered within the error of calculation, are neglected, there was an area of rather large warm differential advection extending to the south of the area in which the tornadoes occurred.

The forecast of differential advection for the approximate time of the tornadoes at Worcester, Mass., and nearby areas on June 9, 1953 (fig. 18), shows the largest negative values to the southeast of the area of tornado occurrence but very nearby. This forecast was made from the 850-mb. chart for 1500 GMT June 9. This case and others in which the computed maximum of future warm differential advection occurs near the area of severe weather indicates that the method used is not always accurate in forecasting the exact location of future storm areas.

Computations of the 850-mb. divergence fields from the actual maps for the times of occurrence of the tornadoes at Flint, Mich., and Worcester, Mass., have been presented by Cressman [10]. His computations showed a line of maximum convergence associated with the tornado development which agrees approximately with the areas of negative differential advection computed above for the same times. Therefore, convergence in the lower levels is confirmed in this case and is consistent with Gilman's [1] hypothesis for the physical processes involved.

The results of these three tornado cases are not sufficient for drawing definite conclusions. However the Hydro-

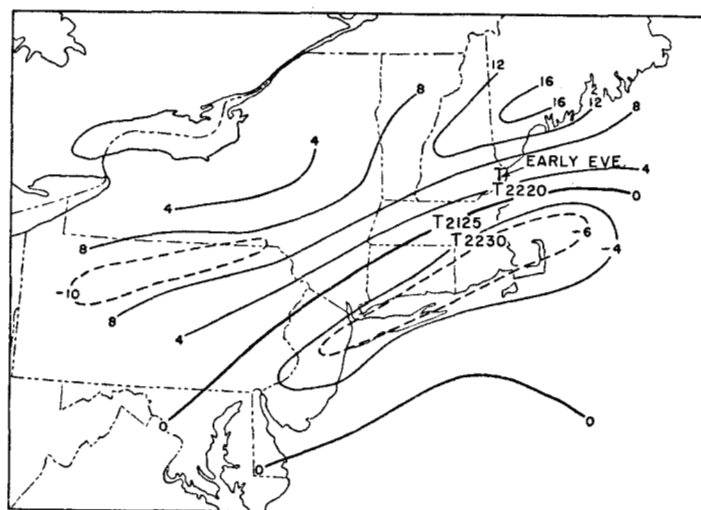


FIGURE 18.—Tornado occurrences plotted on field of forecast differential temperature advection at 850 mb., 1900 GMT, June 9 to 0100 GMT, June 10, 1953. Forecast made from chart for 1500 GMT, June 9.

meteorological Section has made these forecasts on a daily basis during much of the 1954 tornado season and most cases showed areas of maximum warm differential advection within or near the areas in which tornadoes occurred. Moreover, other cases, such as that in figure 9A as well as several which the Severe Local Storm Center worked up while experimenting with this technique, show similar results.

In general the results indicate that the computed differential temperature advection usually has the largest negative values within the areas of most severe weather. It seems that the local maximum of warm differential advection is associated with tornado development. However it is obvious that this is not the only requirement. The absence of latent instability in the atmosphere may account for the failure of the warm differential advection to act as a trigger mechanism in some cases. The use of a 6-hour period for computing the differential advection involved a definite timing problem. However, it is doubtful that shortening the period would alleviate this problem because of the limitations of the temperature field analysis with respect to the size of a tornado. At best the method would suggest probable areas of tornado occurrence when combined with other parameters.

LIMITATIONS OF THE METHOD

It should be pointed out that the differential temperature advection parameter as defined and used in this paper is an average over a period and only where the values are large or continue over most of the period will they show up as definite centers. Because the moisture and stability indices are maxima for the period, occasionally the three parameters are not coincident in time and the forecast area of heavy rain is larger than the observed.

There are several points where caution should be used in interpreting the significance of the forecast parameters. Where warm differential temperature advection is high,

with a low stability index, and low dewpoint, care should be taken to be sure there is not an extremely moist layer just below the 850-mb. level before discounting the possibility of heavy rainfall. Examination of the plotted raobs will provide the answer. When two separate areas of marked warm differential temperature advection, moisture, and instability are forecast, one upwind from the other, the downwind area does not verify. This is not unreasonable, as the temperature field is altered as soon as vertical motions begin in the upwind area. This shows that until the effects of these various parameters on the new temperature field can be determined, the method cannot be extended beyond 24-hour periods. One explanation for its skill in the daily forecasts may be that in cases where rainfall moves in regular progression, the systems are strong enough to replenish the temperature gradients destroyed by the rainfall. In the case where progression is irregular, little vertical motion occurs upstream to destroy the contrasts.

The objection may be raised that only the lower levels of the atmosphere are being considered. Undoubtedly, the inclusion of the surface and the 500-mb. levels would be helpful. However, the greatest moisture transport is above the gradient level [11] (about 925 mb.) and approximately one-half the earth's atmosphere is below the 500-mb. level. Since time is always an important factor in a forecast method, the search is always for the best results with the least expenditure of time.

CONCLUSIONS

From the relations shown in the figures, the basic reasoning of the trajectory method appears to be sound and the method of preparing the trajectories fairly accurate. The indices of the differential temperature advection, stability, and moisture seem to be related to the rainfall mechanism although they are not necessarily the only influences. An attempt is being made to apply statistical methods to determine the relative importance of each factor or combination of factors in the production of heavy rainfall. When this is completed it should be possible to forecast areas of heavy rainfall 12 to 18 hours in advance, with a more definite indication of intensity.

The trajectory method lends itself well to a centralized forecast unit. Although there is a considerable amount of labor involved, it should be pointed out that on many days the possibilities of heavy rainfall can be discounted for a large part of the United States, by examination of the observations. In these cases, trajectories and the parameters need be computed for only a small area. As each parameter is computed it reduces the area for which the other parameters are necessary. When possibilities of

heavy rainfall are imminent, the method could be carried out stepwise for the 12- to 18-hour and 18- to 24-hour periods from each upper-air observation.

ACKNOWLEDGMENTS

I wish to thank Dr. C. S. Gilman for his encouragement and guidance throughout the project, and Mr. George A. Lott, with whom many of the basic ideas were developed and who carried out much of the analysis and testing. Grateful acknowledgment is made to Mrs. L. K. Rubin for her assistance in testing the data and editing, as well as to the entire Hydrometeorological Section, who worked as a team in making the daily forecasts, to typists, Miss Betty Fox and Miss Marian Hammer, and to the Drafting Section for drafting of figures.

REFERENCES

1. C. S. Gilman, Expansion of the Thermal Theory of Pressure Changes, Sc. D. Thesis, Massachusetts Institute of Technology, 1949 (unpublished).
2. C. E. Erickson, Synoptic Characteristics of Extreme Rainfalls, Hydrometeorological Section, U. S. Weather Bureau, Washington, D. C., 1945 (unpublished).
3. H. R. Byers, *General Meteorology*, 1st ed. McGraw-Hill Book Co., Inc., New York, 1944.
4. S. Petterssen *Weather Analysis and Forecasting*, 1st ed. McGraw-Hill Book Co., Inc., New York, 1940.
5. A. F. Gustafson, "On Anomalous Winds in the Free Atmosphere," *Bulletin of the American Meteorological Society*, vol. 34, No. 5, May 1953, pp. 196-201.
6. G. A. Lott, "The Unparalleled Thrall, Texas Rainstorm," *Monthly Weather Review*, vol. 81, No. 7, July 1953, pp. 195-203.
7. A. K. Showalter, "A Stability Index for Thunderstorm Forecasting," *Bulletin of the American Meteorological Society*, vol. 34, No. 6, June 1953, pp. 250-252.
8. Lillian K. Rubin, Trajectory Method Applied to the Louisiana Storm of April 28-29, 1953, Hydrometeorological Section, U. S. Weather Bureau, Washington, D. C., April 1954 (unpublished).
9. M. H. Bailey, Forecast of Differential Advection and Tornado Occurrence, Hydrometeorological Section, U. S. Weather Bureau, Washington, D. C., May 1954 (unpublished).
10. G. P. Cressman, "An Approximate Method of Divergence Measurement," *Journal of Meteorology*, vol. 11, No. 2, April 1954, pp. 83-90.
11. G. S. Benton, M. A. Estoque, and J. Dominitz, "An Evaluation of the Water Vapor Balance of the North American Continent," *Scientific Report No. 1*, Dept. of Civil Engineering. The Johns Hopkins University, July 1953, 101 pp.